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MASTER

PW VUL: A CLASSICAL NOVA WITH NEARLY SOLAR ABUNDANCES*

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ABSTRACT

Ultraviolet and optical spectrophotometric data were combined in order to determine the physical parameters in the expanding shell of Nova PW Vul 1984 #1. Ultraviolet data were obtained with the IUE satellite from August 2, 1984 (a few days after discovery) until it became too faint to study with the satellite. The last IUE exposure was obtained in June 1988 but we have continued to follow it with ground-based optical telescopes. We will present a plot that shows the variation of electron density and temperature as a function of time. Analysis of the emission line intensities show that the abundances of this very slow nova are solar for helium, carbon, and oxygen while nitrogen is 50 times solar. We have also used the CLOUDY code of Ferland to model the emission line intensities and find very good agreement with the observations. We shall display plots of representative IUE and optical spectra.

I. INTRODUCTION

A classical nova outburst originates from a thermonuclear runaway in the surface layers of the white dwarf component of a close binary star. In this model, the secondary star has filled its Roche lobe and transfers matter to the white dwarf, which accretes it through a disk. The deposition of hydrogen-rich material onto the surface of a carbon-oxygen or oxygen-neon-magnesium white dwarf will eventually lead to a thermonuclear runaway (see, for instance, the review by Starrfield 1989). As a result of the mixing of core material into the white dwarf's accreted envelope, the ejecta will be rich in C, N, O, and other intermediate mass nuclei. The actual abundances in the ejecta will depend on the composition of the core, the amount of core material mixed up into the accreted envelope, and other parameters of the white dwarf. It has also been shown that the energetics of the outburst will be sensitive to the abundances of the elements that are mixed up from the core (Starrfield 1989).

In this paper, we study the late development of the emission spectrum of PW Vul (Nova Vul 1984 #2), and use optical and ultraviolet data to derive the changes in the physical conditions of its ejecta with time. We will use these data in order to determine the abundances of the ejected material which can then be utilized to constrain the thermonuclear runaway theory.

II. THE OUTBURST

PW Vul reached its maximum visual brightness of 6.3 mag. on August 4, 1984 (JD 2,445,918; day 7 of the outburst). An optically thick, expanding, pseudo-photosphere was apparent in the ultraviolet spectra obtained near maximum (Stryker *et al.* 1988). A measurement of the infrared light development showed that this photosphere had a black-body temperature of 6700 K (Gehrz *et al.* 1988). Later, over about four months, the density of the ejected material decreased until it became an optically thin shell both in visible and infrared light. In Figure 1, we show a high dispersion spectrum of the region around Hβ in order to demonstrate that this nova exhibits a castellated structure in the emission lines, which is characteristic of most novae, and which indicates that material has been ejected non-uniformly.

Measurement of the double peak observed in the [OIII] 5007Å line (Figure 1) implies that the ionized gas is expanding at about 400 km/sec. At this resolution (150 km sec^{-1}), the profiles break up into at least three major components. The expansion velocity, inferred from the [OIII] line profiles, differs from that determined from He II 4686Å and He II 1640Å suggesting that the latter species may originate in a different location than [O III].

This nova showed both He II 1640Å in the IUE spectra and He II 4686Å in the optical spectra (see the inset in Figure 1). By comparing the observed line fluxes and the theoretical prediction for the flux ratio: He II 1640Å/4686Å (Seaton 1978), we obtained an value of E(B-V) = 0.61 (averaged over a number of dates). The distance was estimated to be about 3 kpc, based on the reddening of stars in the field. This value is consistent with previous determinations. The details of this method and a more complete discussion of PW Vul are presented elsewhere (Saizar *et al.* 1990).

III. OPTICAL OBSERVATIONS

Optical spectrophotometric observations of PW Vul were obtained from September 15, 1985 (day 413), and continued through May 4, 1987 (day 1011), using the Image Dissector Scanner attached to the 1.8-m Perkins reflector of the Ohio Wesleyan and Ohio State Universities at Lowell Observatory. We employed a 600-line-per-mm grating blazed at 5500Å, which covered about 2600Å of the spectrum at 10 Å resolution. A 2.5Å resolution spectrum was also obtained on March 27, 1987, covering the region 4400-5100 Å. The details of the reduction procedures are described by Wagner (1986).

In Figure 2 we present optical spectra obtained on day 413 and day 631 of the outburst. Figure 3 shows an expanded view of the spectrum obtained on Day 413 (September 25, 1985) with many of the weaker features identified. The emission features include both forbidden and permitted transitions, as well as high and low ionization. The strongest emission lines are those due to [O III] 5007Å and Hα. Weaker permitted lines are due to other members of the Balmer series of H, and also to He I 4471Å, 5876Å, 6678Å, 7065Å, He II 4686Å, 5411Å, N III 4640Å, and N V 4600Å. The strongest forbidden lines arise from [O III] 4363Å, 4959Å, 5007Å, [OII] 7320Å, 7330Å, [NII] 5755Å, [NeIII] 3869Å, 3968Å, and others. In the later spectra, we observe [NII] 6548Å, 6584Å as structure in the

Hα profile. Some coronal lines are also present, such as [Fe VII] 6087Å, and [Fe X] 6374Å is inferred from the anomalous ratio of [OI] 6300Å to [OI] 6363Å.

The absolute strengths of the emission lines decrease quickly with time. The relative strengths also change with time and indicate that the physical conditions in the ejecta are evolving with time. For example, the [OIII] 5007Å to Hα ratio increased by about a factor of 2 between days 413 and 1011 even though the total flux of [OIII] had decreased by a factor of 16. Other changes in relative line strength produced by the decreasing density of the emission region, include the rapid decline of [N II] 5755Å and [OIII] 4363Å.

IV. ULTRAVIOLET OBSERVATIONS

Ultraviolet observations of PW Vul with the IUE satellite began on August 2, 1984, two days after discovery and continued until June 23, 1988. Unfortunately, many of the early spectra were overexposed as the ultraviolet flux was increasing rapidly. An ultraviolet light curve for this nova can be found in Austin *et al.*(1990; these proceedings). We shall discuss the early spectra elsewhere, here we concentrate on two of the late time spectra that are suitable for abundance determinations from nebular emission line analyses. In Figure 4, we display combined short wavelength prime (SWP) plus long wavelength prime (LWP) spectra obtained during the same shift for days 253 and 331 of the outburst.

As seen in the optical, the spectrum at late times contained a mixture of both high and low ionization lines with both resonance and intercombination lines present. These spectra are very similar to the emission spectra of high redshift quasars. We find that NIII]

1750Å and NIV] 1486Å are present during the entire late time evolution of this nova indicating that the electron density had fallen to below 10^{11} cm^{-3} by April 1985. The presence of NV 1240Å indicates a strong ionizing continuum which is borne out by the **EXOSAT** detection of PW VUL in June 1985 (Ögelman, Krautter, and Beuermann 1987). The strongest lines are NIV] 1486Å, CIV 1550Å, N III] 1750Å, C III] 1909Å, C II] 2326Å, Mg II 2800Å, and OIII 3133Å. The region between about 2000Å and 2400Å is underexposed on both spectra and shows the noise level at the short wavelength edge of the LWP camera.

Figure 4b was obtained on June 24, 1985 and while the emission lines are steadily decreasing in strength, they appear to be retaining virtually the same ratio of intensity. However, Mg II 2800Å has dropped much faster than CIV 1550Å. At first glance, the strength of CII], CIII], and CIV would suggest that carbon was enhanced in the ejecta. However, they are strong only because of the characteristics of the shell and not because carbon is enhanced in abundance which suggests that one must be careful in interpreting line strengths as indicators of enhanced abundances. Finally, note the presence of N V 1240Å, which suggests the presence of a strong ionizing continuum.

V. PHYSICAL CONDITIONS IN THE EJECTA

The spectra we have just presented show emission lines typical of the nebular phase of a nova. We have seen that the flux of a recombination line like Hβ decreases with time.

This is due to the decrease in the electron density as the shell expands, if recombination is the dominant process in the nebular region. The temporal development of some [OIII] lines is shown in Figure 5. Note how the relative intensity increases with time, as the electron density decreases and, thus, radiative cooling dominates over collisional de-excitation of these ions. This behavior is very different from that seen in the evolution of QU Vul.

The set of [O III] lines, $\lambda\lambda$ 4959Å, 5007Å, λ4363Å, and $\lambda\lambda$ 1660Å, 1666Å, can be used to measure some of the physical parameters in the nova shell, by applying standard techniques of nebular physics (Osterbrock 1988). The equations of statistical equilibrium let us write the intensities of these three lines relative to $H\beta$ in terms of the electron temperature and density and the relative ion abundance. A full derivation and an estimate of the errors involved, mainly due to uncertainties in the reddening, is discussed elsewhere (Saizar *et al.* 1990).

Our results suggest that $T_e \sim 13{,}000$ K and N_e falls from about 4×10^6 cm^{-3}, 11 months after the outburst, to about 10^4 to 10^5 cm^{-3}, one year later. Once the electron temperature and density are known, one can derive the abundances for most elements from the relative intensities of the emission lines. However, some assumptions must be made concerning the relationship between ion and total abundance. For example, we assumed that O/He $\sim$ O^{++}/He^{++}, since both elements have about the same ionization potential and are probably located in the same region (i.e., at the same temperature).

We find that the ejecta have approximately solar composition, with the exception of nitrogen, which is significantly enhanced by a factor of ~ 50 over solar material. Typical errors of about 2,000 K in the temperature and 0.5×10^6 cm^{-3} in the density imply factor of two errors in the abundances. A high nitrogen abundance is to be expected if carbon was mixed up from the core into the accreted envelope and was then burned to nitrogen via high temperature CNO burning (Starrfield 1989).

We also find that the ejected shell is rather massive for a nova. Using the Hβ emission measures and a detailed study of the coronal line region (Saizar *et al.* 1990), we find an ejected mass of $\sim 3 \times 10^{-4} M_{\odot}$. This value is so large, that we predict that the white dwarf component of the PW Vul system will have a mass of about $1 M_{\odot}$.

VI. CONCLUSIONS

The use of both **IUE** and ground-based spectra has allowed us to determine the abundances in the ejected nebular shell of PW Vul. Errors arise mainly from uncertainties in the reddening and the lack of simultaneous IUE and optical data. However, our results show a clear enhancement of nitrogen and, possibly, oxygen over solar values. Although neon and magnesium have been reported to be enhanced in some other novae (Gehrz, Grasdalen and Hackwell 1985), they do not seem to be enhanced in PW Vul. This implies that the underlying white dwarf is a CO white dwarf and not an ONeMg white dwarf. The abundances are consistent with a very slow nova.

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CAPTIONS FOR FIGURES

Figure 1. High dispersion spectrum obtained on March 27, 1987. The line widths indicate an expansion velocity of ~400 km sec^{-1}. The inset shows the line profiles of NIII 4640Å, He II 4686Å, and Hβ.

Figure 2. This figure shows the optical spectrum on September 25, 1985 and April 20, 1986.

Figure 3. This figure is an enlargement of the spectrum on September 15, 1985 showing the principal emission features. Note the presence of both permitted and forbidden lines of both high and low ionization.

Figure 4. IUE spectra of PW Vul obtained on April 7, 1985 and June 24, 1985. The line identifications are in the text.

Figure 5. This figure shows the evolution with time of the ratio of [O III] (4959Å + 5007Å)/ [OIII] 4363Å.

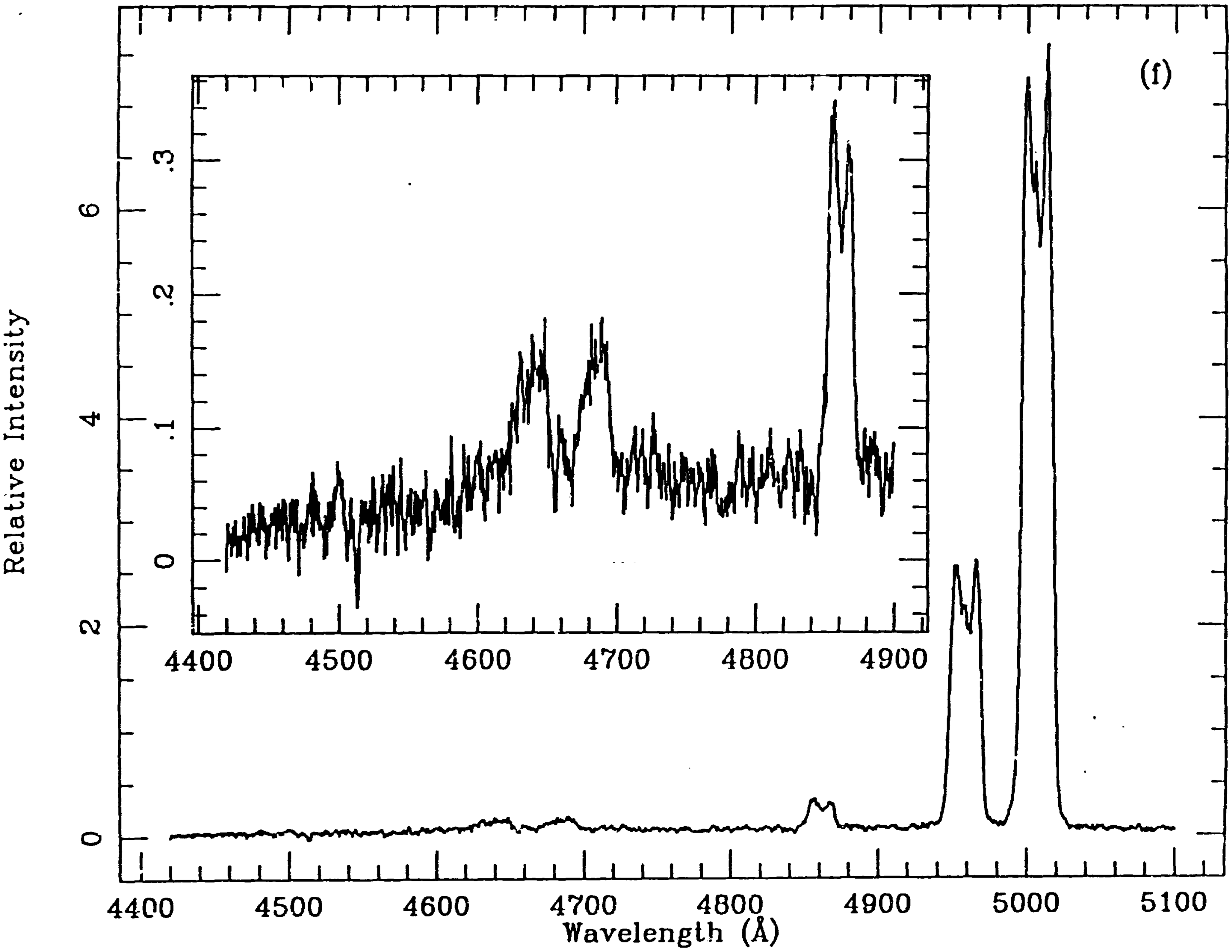

(f)
Relative Intensity
0
2
4
6
.3
.2
.1
0
4400
4500
4600
4700
4800
4900
4400
4500
4600
4700
4800
4900
5000
5100
Wavelength (Å)

Figure 1

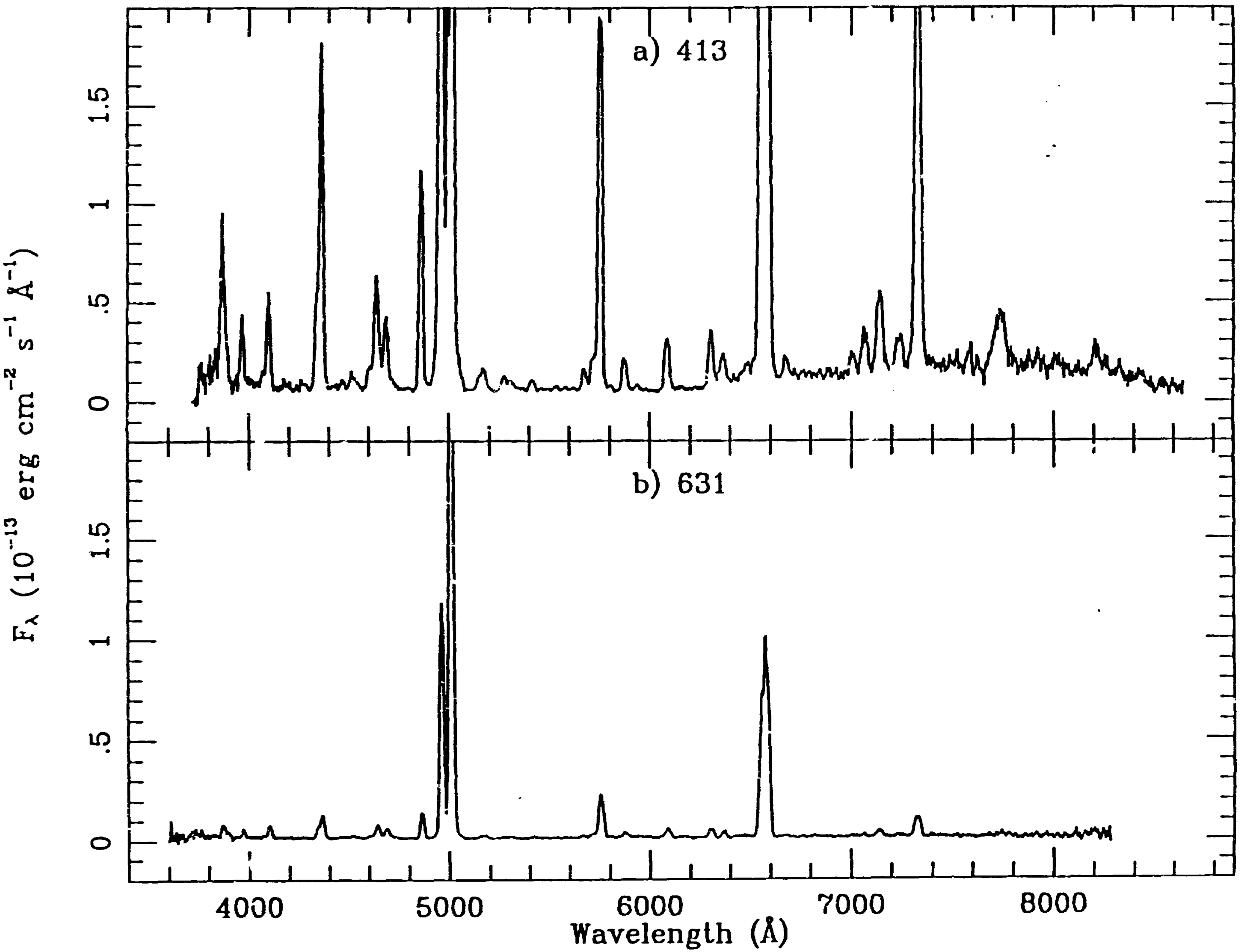

a) 413
b) 631
F_λ (10^{-13} erg cm^{-2} s^{-1} Å^{-1})
0
.5
1
1.5
0
.5
1
1.5
4000
5000
6000
7000
8000
Wavelength (Å)

Figure 1

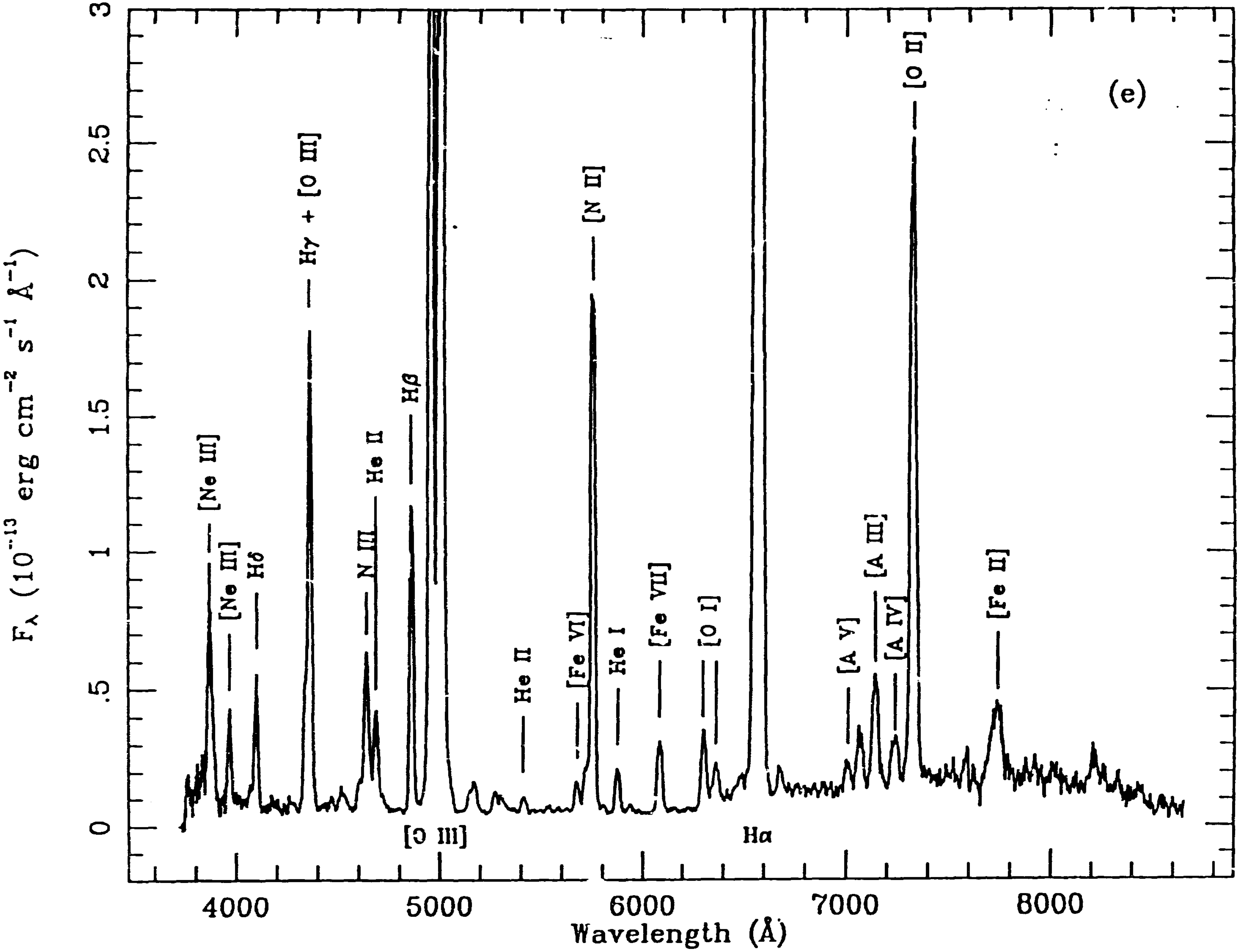
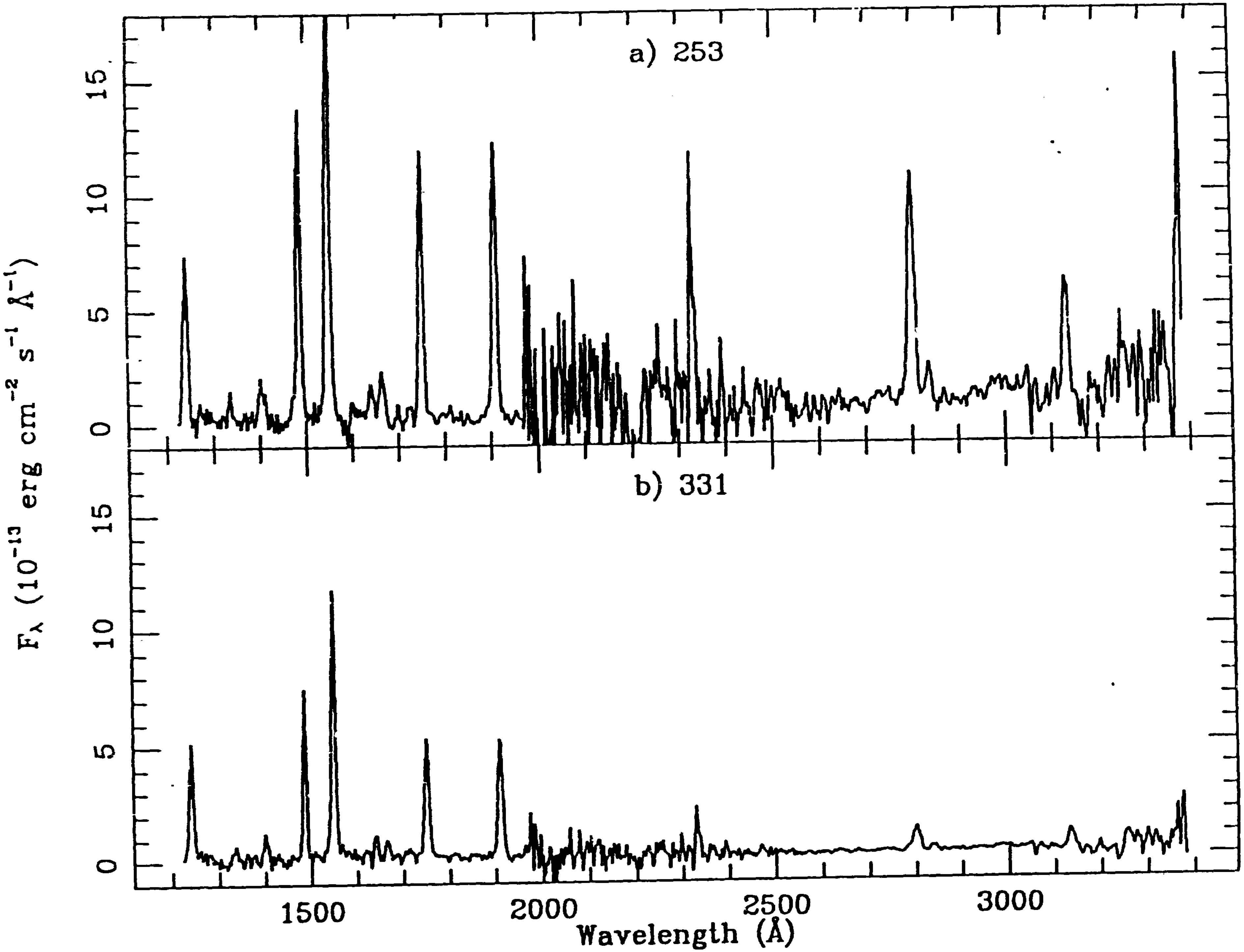

(e)
[Ne III]
[Ne III]
Hδ
Hγ + [O III]
N III
He II
Hβ
[O III]
He II
[Fe VI]
[N II]
He I
[Fe VII]
[O I]
Hα
[A V]
[A III]
[A IV]
[O II]
[Fe II]
F_λ (10^{-13} erg cm^{-2} s^{-1} Å^{-1})
0
.5
1
1.5
2
2.5
3
4000
5000
6000
7000
8000
Wavelength (Å)

Figure 1


a) 253
b) 331
F_λ (10^{-13} erg cm^{-2} s^{-1} Å^{-1})
0
5
10
15
0
5
10
15
1500
2000
2500
3000
Wavelength (Å)

Figure

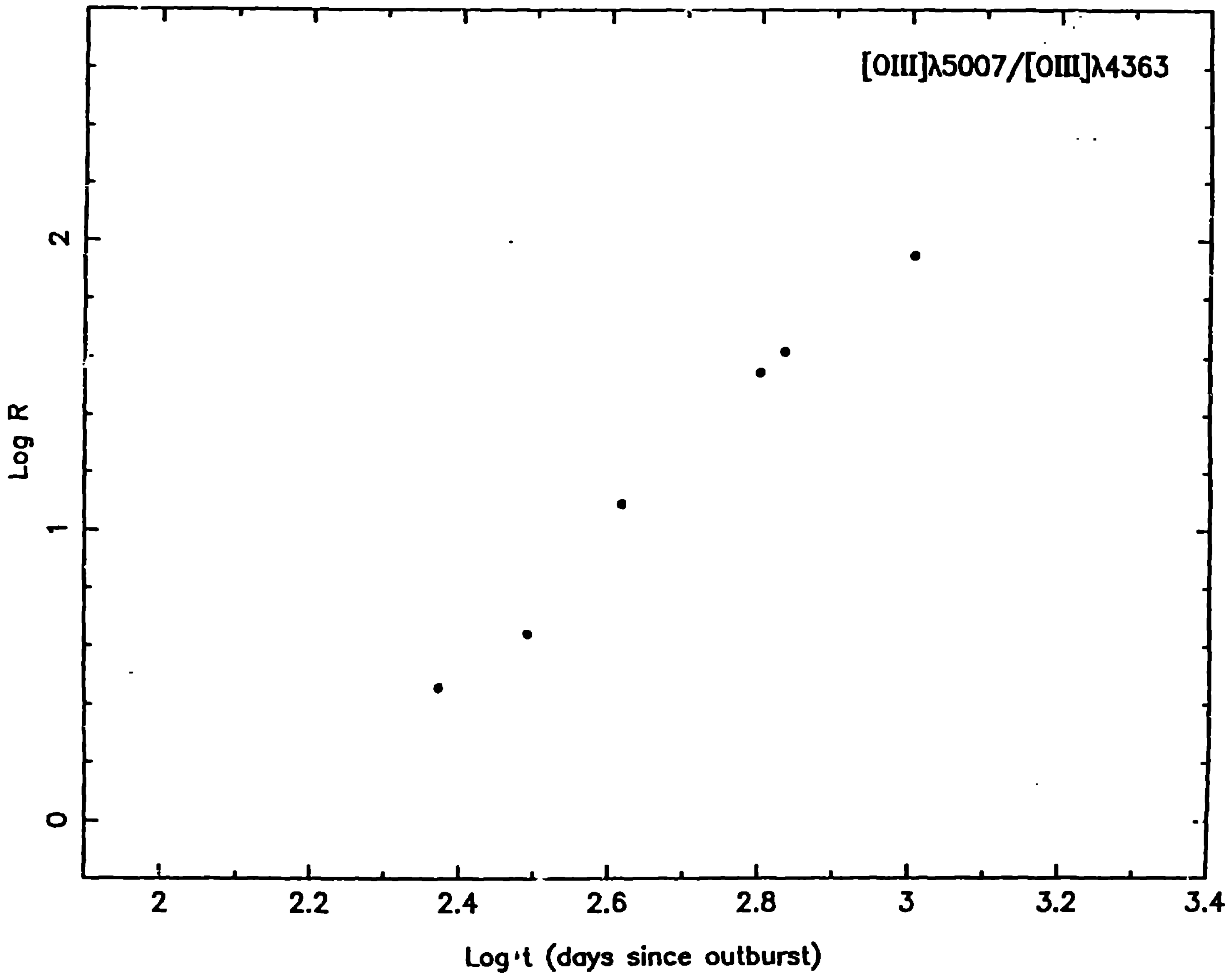

[OIII]λ5007/[OIII]λ4363
Log R
0
1
2
2
2.2
2.4
2.6
2.8
3
3.2
3.4
Log t (days since outburst)

Figure 5